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Hybrid renewable energy systems for off-grid electric power: Review of substantial issues

Y.S. Mohammed [a,*], M.W. Mustafa [a], N. Bashir [b]

[a] Department of Electrical Power Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia
[b] Institute of High Voltage and High Current, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia

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A B S T R A C T

A hybrid power system is an emerging power generation technique which involves a combination of different energy systems, mostly renewables for optimal output configuration. In modern pursuit for renewable energy (RE) development, optimum conditions for the production and utilization of energy system are considered to be an indispensable feature for economic load dispatch. This is a rationalizing fact taking into consideration the rising price of energy for socio-economic development. Therefore, this paper reviews primary issues regarding the drivers and specific benefits of hybrid renewable energy systems (HRES). Moreover, this paper presents discussions on the various renewable energy sources which can be explored for HRES implementation. Finally, the framework unfolds a vivid review on factors to be considered for designing and implementation of HRES in general including simulation and optimization software packages for making such analyses.

Contents

* Corresponding author. Tel.: +60149905273; fax: +6075578150.
E-mail address: engryek88@yahoo.com (Y.S. Mohammed).

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1. Introduction

Currently, global energy consumption at all level of society development has considerably increased in the last few decades. However, several interesting numbers of contemporary literatures have confirmed scenarios of continuous increase in energy demand based on the progression of socio-economic activities. This step up in demand for energy may possibly be attributed to increasing quest for socio-economic sustainability in developed regions and industrialization in developing countries. Electricity is one of the core factors to all forms of development in the present day. For instance, a micro-economic activity at rural level such as small scale agricultural production is convincingly and progressively in need of modern energy for continued existence in line with modernization tendencies. Thus, in most rural areas of developing countries, grid connected electric power supply is economically not realistic due to high cost of paying for the energy amid constricted energy potential of the inhabitants. Supply of electricity with diesel based fuel becomes very much expensive while hybrid/photovoltaic/wind generation becomes competitive with diesel only generation [1–3].

Technologies utilizing single energy generation systems such as solar, wind, biomass, geothermal, hydropower and diesel only have well-known history in the context of global energy development. Without doubt, electric power generation evolved from the utilization of single energy system. Varieties of energy production systems comprising of a single source of heat energy scheme have been studied in the research works [4–7]. In [8–12], solar based energy generation using vacuum-tube collectors, solar storage system and solar water heating systems have been reported. Some other literature sources based on solar energy [13–16] applications have confirmed the usefulness and viability of the technique for electricity generation. Barry and Attilio published a research article on the application of biomass gasification only for electrification in Vanuatu [17] and the Malaysian case studies using biomass residue from oil palm [18] and banana [19]. In India, Purohit [20] presented a study on the economic potential of biomass power project using gasification under a clean development mechanism of the Kyoto protocol. Off-grid and grid-connected energy systems using wind power turbines alone have been exploited by research and development [21–26]. In a similar technique of single energy system utilization, hydropower [27–32] is as well being used single-handedly for electricity generation. Emerging technologies of electric power generation is essentially advocating for combinations of different resources for efficient and quality power delivery especially on the utilization of different kinds of renewable sources thereby causing some paradigm shift of attentions from single energy system application for electricity generation to combinations of energy systems called hybrid power technologies. Hikmet et al. [33] reported an experimental evaluation of using different kinds of renewable energy sources for heat energy production. In most cases, the end product of a hybrid energy system can be heat, electricity or heat-electricity using a combined facility known as cogeneration. Hybrid electric power systems is a mechanism that explore multiple sources of energy connected together to achieve synchronized power output. Nowadays, the uses of hybrid energy system are tremendously working in favor of renewable energy system exploitation. Notably, a HRES has enormous potential to provide quality, secured and reliable electricity to the consumers especially on micro-grid operations for remote locations.

Various research works [34–36] have confirmed that HRES in off-grid applications are economically workable, mainly in remote locations. In some cases, rather than being on economically competing track with a diesel based power supply system, a combination of different systems to form a hybrid system is more reliable in producing electricity, and often presents the best solution for electrifying remote areas [3]. Fig. 1 presents an

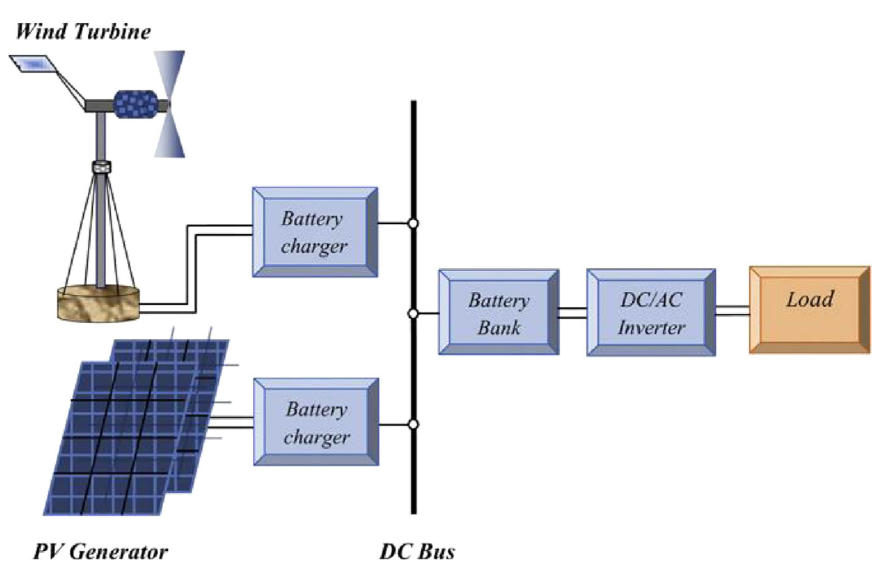


Fig. 1. Block diagram of a hybrid PV/wind system [38].

illustration of a simple hybrid power system utilizing wind turbine generator and a PV system. Presently, a renewable based hybrid energy supply system is becoming a widespread engagement in energy sector. Since some renewable energy sources (RES) are closely associated with intermittency, therefore a combination of more than one of the resources may be helpful towards eliminating the related variability. Up to this moment of time, there is no single definition of hybrid electric system (HES) because so many researchers have attempted describe it based on their understanding of the concept. A hybrid power system is defined as an off-grid electric power generator system comprising of more than one energy generation source and the end-use energy is basically electricity [37]. In furtherance, hybrid system for electric power generation is fundamentally a productive means of enhancing sustainable development in electric power industry. It is an optimum emissions reduction technique. Emissions of greenhouse gases (GHGs) from power generation and energy consumption can be minimized using electric power hybrid network. Promoting the sacredness of sustainable development is a direct affirmation of prominent international communities and organizations as prominently promoted in Kyoto Protocol. In ideal perspective, sustainability is an integration of several conceptions ranging from policy creation to engineering creativity. In recent time, the promise held by the tendency for the implementation of hybrid power systems in energy sector has pave attractive ways to generate electricity on both small and large scale using RES. The individual downside of different RES can be eliminated by promoting hybrid power system application for electric power supply in a most cost-effective logic. Besides, electricity generation is also highly connected to system efficiency and economic dispatch scenarios, and then an optimum combination of different RES is a crucial issue. Therefore, this article review some integrated issues concerning hybrid power system implementation based on the conception of developing countries.

2. Literature review

The goals of the scores of countries across different regions of the world especially the economically emerging countries are to provide economically affordable and environmentally friendly energy to their citizens. This quest is usually one of the greatest priorities of central government for the people residing in local and remote areas of developing countries. Over 1.6 billion people in the world lack access to electricity and approximately 80% reside in rural Asia and Africa [39,40]. Also, because of the rise in the level of energy consumption across the global and on the other hand some reports of decline in the level of accessibility to energy, researchers and energy experts have found the need to provide alternative methods of energy production. This situation, from focal point of view has thrown up support for RE exploitation in some developed countries in a more economical way using HRES. Though, RE such as wind, solar and biomass power have presented a very significant research interest in the field of energy but hybrid power system application using RE systems has been a research area of interest with limited number of publications. HRES is still an ongoing research hot spot especially to RE experts and electrical power engineers. In this line of study, it was stated that solar radiation and wind are comprehensively the most favoured RES for their availability and inexhaustibility [41]. In hybrid system, an integrated PV system, wind energy system and a battery units sharing DC-bus [42] and AC-bus arrangement [43] supplying energy to a load in the absence of utility grid can be configured to supply electricity. In reality, other RES like hydro, biomass and hydrogen have also been used including fossil fuel-based based back-up systems (e.g. diesel). Nixon et al. [44] conducted a study on the feasibility on hybrid solar-biomass power plant implementation in India. The paper investigated different criteria of economic, environmental and technical issues concerning electricity generation and process heat production using simulation models. Conclusion drawn from the study established that the hybrid system is highly cost saving compare to a single RE energy for power generation. Afgan and Carvalho [45] conducted a study on sustainability consideration for hybrid energy systems. The article unfolded some levels of indicators used as measured factors for sustainability assessment towards hybrid power systems implementation. The indicators are economic indices, social acceptability and environmental portfolio.

Getachew and Gelma [46] designed a hybrid system comprising of photovoltaic-wind system for power generation for a remote community in Ethiopia. In their work, a software tool was used to analyze data concerning the potential of solar and wind in the case study area. Furthermore, emergence of hybrid power systems has also enhanced the exploitation of energy storage systems to boast the availability of electricity to potential users. Authors in reference [47] studied the needs, opportunities as well as challenges for RE hybrid energy storage systems. The study discusses different types of energy storage systems and strongly acknowledged incorporation of an energy storage system into a hybrid power system especially for elimination of intermittency. Specifically, the study focused on the review of some possible problems related to energy storage in hybrid power systems, modeling and simulation techniques required for the performance analysis of the system integrated elements. In another study conducted by [48], efforts were rationalized to unveil the characteristic of integrating different kinds of RE systems (solar cell (SC), wind turbine (WT), fuel cell (FC) and ultra-capacitor (UC) systems) for power generation. Numerous literatures [49–56] have also focused on the use of RE based hybrid power system.

3. Drivers for hybrid renewable energy systems development

3.1. Economic factor

Presently, there is a global experience of economic problem. The challenge has in a wider perspective affected so many facet of modern development. The price of energy from fossil based power generation has been affected by the fluctuations in the price of oil and gas at various instances. This problem of price shock has been caused by different factors such as regional agitations, government policies, internal conflicts in different countries and integrated economic uncertainties. In most rural communities of developing countries, electricity supply has been sustained by the use of diesel-based generators [40]. The attendant operating and maintenance cost [51–59] have been worrisome economic factor. Therefore, economic challenges couple with logistic constraint such as transportation have hindered the application of RE systems. Ideally, power is supposed to be generated as and when needed but solar and wind energy systems do not meet this requirement. Wind source and solar radiation are not always available. However, the combination of both can give optimum economic condition compared to using just either for power generation. From economic point of view, a PV stand-alone system is little far from being economic compare to conventional fossil fuel electricity [40,60,61], but they are used in isolated areas where it is uneconomical to extend the electric grid [36,62]. PV-based hybrid system (using wind and/or diesel generator) is an option to deal with this barrier and supply electricity to rural areas that are not close to the grid system [40,58,59,63–67]. Therefore, the economic potential of hybrid energy systems is

satisfactorily promising to integrate them into the power sector of developing countries.

3.2. Shortage of electric power supply

Currently, shortage of electrical energy has been a widespread experience in many developing countries. Insufficient generation can result into frequent power outage conditions and rationing of energy supply. Limited access to energy can bring about straining of livelihood. This problem is not in actual sense due to lack of energy resources but can be attributed to other factors like incomprehensive planning and management of resource, poor energy policies, economic challenges and constraints in energy financing and implementation models. The challenges of energy deficiency have been resolved in many rural and remote communities including urban cities using renewable energy systems and HRES.

3.3. Environmental perspective

These days, Environmental Impact Assessment (EIA) has been an issue of front burner as related to the scene of energy sciences. The reason is that there is a strong relationship between energy-induced actions and a climate change factor. Production of fossil-based energy give-off greenhouse gases (GHGs) with increasing impacts on rising of global warming potential. In this present showdown of economic reality, it is imperative that practices related to climate change mitigation make good economic senses to avoid huge expenditures. Climate change [68–70] is an alteration in the condition of the climate which can be identified by changes in the mean and changeability of its properties that persists for extended periods of decades or more. The danger of climate volatility will have a global impact and no country on its own can resolve it [70] because of the centrality of the global atmosphere. A more appropriate solution lies on the tendencies to synchronize national actions as contained in regional and international frameworks [70]. Confrontation pursuit against environmental hazards orchestrated from energy calls for different plan of actions. Such plan should be long-term [71] in nature, be proficient to act in response to uncertainties and unplanned events, as well can be adjusted to suit new information as they turn out to be identified [70]. One of the most suitable and unanimous solutions already propounded is the development of RE [72] in a more effective way, perhaps involving hybrid-based RE energy systems.

3.4. Socio-political demand

Sociology of mankind could be said to be one of the key drivers encouraging hybrid power system for RE exploitation. Necessities for social development as adjudged by the needs of people in a society are worth considered and must not be compromised especially if it is vital to ensure sustainability. This is the case of electrical energy which is almost central to all forms of modern development. In addition, prevailing democratic systems are also an advocate of progressive development in our modern society. New generation of political leaders is exploring opportunities for political agenda, economic reforms and infrastructural development of power sectors to ensure that electricity is made available to all irrespective of the region. In reality, if reasonable part of this aspiration is achieved, then the gap in the social divergence between the urban and rural populace could be reduced drastically.

3.5. Increasing renewable energy subsidies

Energy subsidies are transactions that maintain prices for consumers or producers less market points or reducing costs for consumers and producers by direct or indirect cash transfer apparatus. IEA [73] view energy subsidies as an artificially created mechanism to lower the price of energy paid by consumers, raise the price received by producers or lower the cost of production. Subsidies to RE and low-carbon energy emission technologies can convey long-term economic and environmental benefits [73]. Currently, a high level of subsidy provision is being envisaged for RE development across different regions of the world as a strategy for cut carbon emissions. A wide range fact regarding RE subsidies issue is that developing and developed countries exhibit a greater variation in subsidy provided. In the last period of a decade or more, RE sustenance provided in the form of subsidies for development, research grants, feed-in tariffs, and provision of capital for investment has accounted for the explosion in RE investments.

It is however crucial to mention that the leading financial variable in most cases is the subsidies for developing countries from developed nations. Industrialized countries that use more of fossil based energy resources to power their economy make some compulsory donations to the developing world for RE development. This is fashioned in accordance with the rules of the United Nations Framework Convention on Climate Change (UNFCCC). Though, much has not been achieved from this structural tradeoff for GHGs emissions. Ordinarily, the idea is to tilt the stage ground to the gain of developing countries to embark on long-lasting RE development. The fundamental prospect is cutting carbon emissions which some private establishments and government institutions alike have seen to be imperative. Notwithstanding, this has made subsidies available from local and national government, Non-governmental organization and international development agencies to strengthen cash flow for RE.

3.6. Availability of renewable energy resources

Supplying power to areas without access to grid system is a difficult task. In this case, an autonomous RE power supply has been a meaningful alternative power supply scheme. This is typically the case where supplies of foreign fuel to such locations involve logistic difficulties with associated high cost. Renewable energy sources (RES) are made of varieties of energy sources such that at least one of the sources can be found at a given geographical location. RES can be found in sustainable quantity in any region even those with high challenges of techno-economic prosperity. RES are naturally endowed energy resources. Examples of RES are wind, solar, hydro, geothermal, biomass and waves. Among the RES, biomass has more source components with different technological options for energy conversion and greater diversity for energy use. Within the framework of hybrid power system, two or more different biomass resources can be used with other RES.

3.7. Renewable energy policy

Renewable energy policy is a central driver towards the growing pursuit for RE utilization. There is an increasing number of countries around the world are establishing policies on RE integration into the power sector. Such policies differ from country to country with some fashioned out as national targets for RE. Renewable energy policy is currently not limited to national or regional government alone, but a wide range of state-wise and local based policies have also emerged in recent time. Policies have been helpful on the subject of RE commercialization and market orientation. From country to country, there is a tendency for

similarity in the challenges confronting RE development. In addition, it is possible that the manners of addressing the problems may be differed based on economic perspective, technological orientation and workability of policy frameworks. Needs for creating more jobs for economic improvement is also pleasing to the eye thorough RE policies development and implementation. This rely on the fact that jobs from RE occur in hundreds of thousands in several countries [74]. Continuous change in the development of RE from time to time in different countries is realistically expanding RE capacity using single or hybrid (combine) systems. From this point of view, regional geography of RE development continues to change with respect to the practical implementation of policy framework.

3.8. Utilization of energy storage systems

Energy storage systems (ESSs) are used for transforming electrical energy from a power network into a form that can be stored for reverting back to electrical energy when needed [75–77] for serving some anticipated purposes. At present, varieties of options exist for energy storage systems (ESSs) selection. Storage systems are now being considered as an integral part of the facilities for RE distributed generation (DG). Different kinds of energy storage systems for small and large power exploitation are presently in use across different regions of the world. A number of ESSs benefits in power system application have been acknowledged [3]. These benefits include grid stabilization, power quality management, reliability supervision, loads shifting and grid operational supports. The reality of ESS functions had encouraged the government of many developed nations like EU [77–80], United States [81–85] and Japan [78,86] to initiate some support measures for storage system application in electric power industry. In general, the application of ESSs will continue to grow as more thoughts are concentrated on RE development due to accelerated depletion of fossil fuels. Conventionally, electrical energy produced needed to be consumed instantaneously or else it will be wasted causing some wanton economic setback. Intermittent RE sources like wind and solar cannot be stored in the absence of ESSs and must be used when available or else they will be lost energy potentials [3].To counteract this problem, there are obligatory needs for ESSs incorporated into hybrid systems which are to be charged at off-peak period and discharged at the period of high demand.

4. Benefits of hybrid power system

4.1. Boasting power system integration methods

Optimistically, varieties of system utilizing RES for electricity production will be emerging in future. Increasing use of RE systems is directly connected to two things which are shortage of energy from conventional sources and prevalent global intention for power sector decarbonization. Therefore, any method enhancing better integration for RE into power sector is highly a welcome development provided it can be operated within the ambient of economic justification. HRES has been suggested as one of the emerging power system integration methods. Incursion of this method is also part of the systems augmenting plans of actions to guarantee effective generation mix to combat energy crisis in any part of the world.

4.2. Increase in the reliability of RE exploitation

In most cases, a single RE system used for electricity generation may not guarantee sufficient reliability. This is due to non-linear characteristic of some of the components. Discontinuity connected to the uses of single RE system is without a doubt tie to reliability challenges. For example, a solar PV based lighting system exhibits low performance characteristics under a cloudy weather condition. To improve performance, establish methods for accurately forecasting their output and reliably incorporating them with other conventional sources [41] should be explored. As part of this effort, optimally design hybrid systems can be used to maximize energy captured from the combination of different RES. With proper system optimization, integrated RE systems with reduced intermittent characteristic can be cost-effective and have better operational reliability.

4.3. Viable rural electrification option

Rural electrification is a well-known concept in developing countries. Electricity supply to rural villages of developing countries is highly insufficient such that majority of the human population lack access to modern energy. The phenomenon of energy deficiency is more pronounced among the remote rural areas of African sub-regions of sub-Sahara [87–89] as illustrated in Fig. 2. These isolated rural districts in developing countries have miniature prospects to access grid-based electricity. Grid electricity is usually for large customers residing in cities and electricity supply to urban households is justified with their economic potential to afford payment for the heavy expenditure for electricity infrastructure. In the last few decades, several research studies including [89] have advocated for RE development as alternative solution to rural energy deficiency. Therefore, as a best possible approach for RE energy utilization, hybrid energy system for rural electrification is decidedly becoming attractive due to their tendency to resolve some realistic economic dispatch problems related to small power generation.

4.4. Influencing the development of advanced power electronics interface technology for harvesting energy

The technology of power electronic has experienced outstanding technological advancement because of the development of fast response and high power semiconductors as well as real real-time controllers with the ability to manipulate complex control algorithms working in a robust environment [90]. For RE development, PE such as advanced motor drives serves as a vital part connecting RE systems to the main grid. Further, power system automation, energy network interfacing, isolation, protection and conversion are really contributing to the growth and diversity in the trend of PE technology development. In this perspective, PE transacts with energy conversion, control and monitoring applications in power system network exploring renewables by means of switching semi-conductor devices as illustrated in Fig. 3. Hybrid power system involves configuration of different RE systems for maximum power output. A hybrid power system involving wind and solar energy systems may use maximum power point tracking (MPPT). In PV system, this could help in optimization for extracting the maximum power output of the PV array [91–110]. Also, design and operation of MPPT use technologies of PE especially in the midst of the accessing low-cost microcontroller and field programmable arrays. Different kinds of MPPT such as perturbation and observation method and incremental conductance methods have been developed and widely used for such systems [90].

4.5. Resolution of RE intermittency

RE intermittency is characterized with uncertainty and variability which is one of the major sources of difficulties in analyzing power system performances. A major distinction between

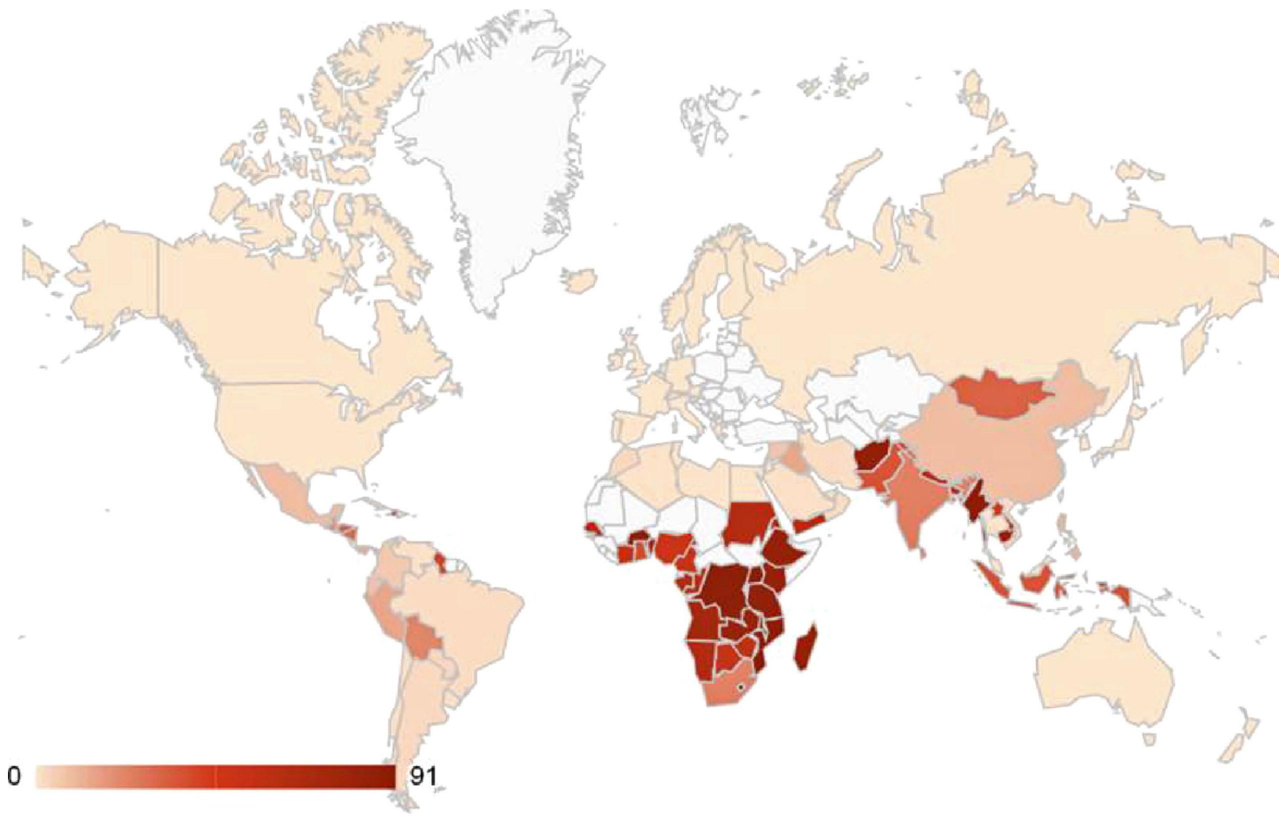


Fig. 2. Percentage of population without access to electricity [87–89].

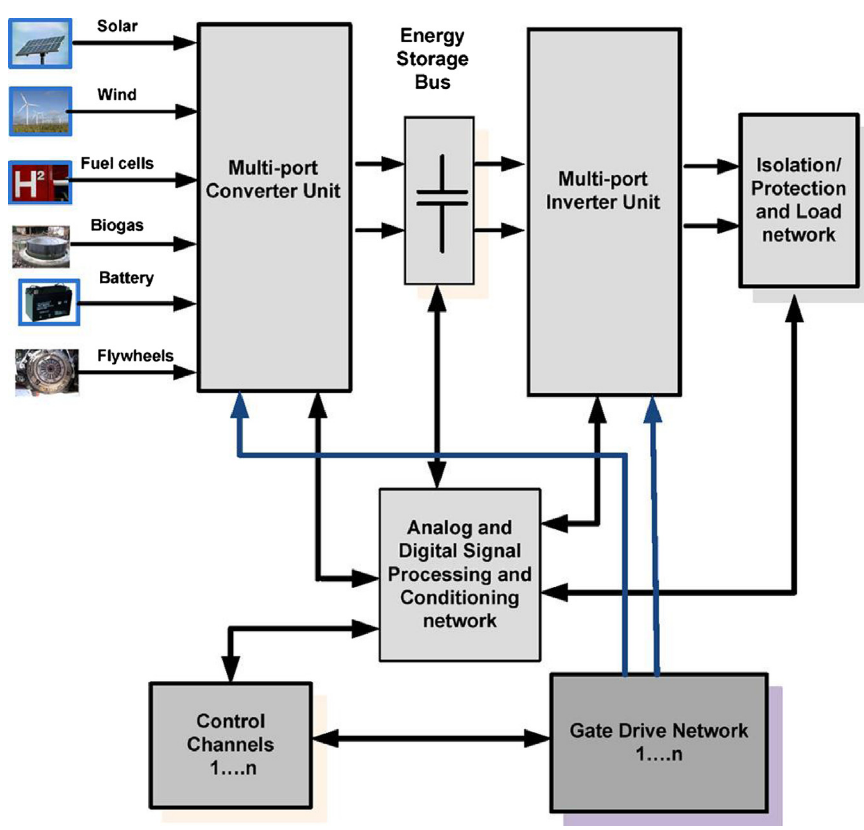


Fig. 3. Hybrid renewable energy sources interconnected and their control algorithm [32].

conventional and non-conventional (renewable) energy systems is largely depending on the rate of occurrence and the scale of the fluctuating tendency. Some kinds of RE systems are highly linked with intermittent trends as contrary to conventional power supply from fossil based power plants. This observable fact is illustrated in Fig. 4. Solar and wind power exhibits certain degree of

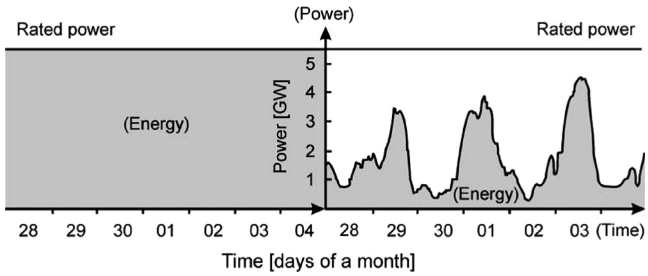


Fig. 4. The difference between an intermittent and a non-intermittent energy source of equal installed power. The left part illustrates the ideal case of a non-intermittent energy source. The right part illustrates an intermittent energy source and is an example from a week of wind power generation in the E.ON controlled grid 28/4-4/5 2003 [111,112].

intermittency across different regions of the world. A fundamental advantage of non-intermittent electricity is that opportunities exist for stable power supply to grid systems. This depends on their ability to generate electric power whenever it is needed. This tendency whereby conventional power system runs continuously makes them a widely preferred option by the majority of electricity users in the world. Availability of strong wind in one region compares better than others and, in addition, variation in the intensity of sunshine between a tropical and temperate climate adjudges the differences in exploitation index due to fluctuations in atmospheric conditions. Hydroelectricity generation can also be linked with variability due to seasonal changes in rainfall intensities. Since RE bring opportunities for development to rural and isolated areas, the reality of the benefits which could be achieved if a more integrated system is sustained especially to counter the inherent fluctuating characteristic of the systems should not be ignored. Besides the need for flexible back-up (energy storage systems), optimally configured hybrid systems could also guarantee technical resolution of problems related to RE intermittency.

5. Sources of RE with potential for hybrid power system utilization

5.1. Biomass

Biomass is all living organic matters with trend of being used for energy purposes. There are three major compositions of biomass resources which are agricultural waste from crop residues; biodegradable wastes from industrial sludge, dung and food waste; and forest bioenergy resources. Up till date, biomass is still being used as a basic source of energy using varieties of traditional methods in developing countries. In the great effort towards switching from non-renewable to renewable electricity, biomass is one of the promising sources of energy. Technical and economic viability of biomass is still under proving circumstances in different countries of the world. Varieties of energy production systems are available using biomass for power generation. Biomass can be subjected to processes producing heat or steam for electricity as well as other useable energy resources such as biodiesel, bioethanol, biomass pellets and bio-methane gas. In some countries, existing trend includes combined heat and power (CHP) on a building or community scale mainly for electricity or district heating applications [113]. Using biomass for energy generation still largely depends on index factors such as system efficiency, resource availability, social acceptability, emission factor, land use policy, technology, economic cost of power plant and fuel flow. Some constraints such as socio-economic adversity of land and water usage [114] couple with soaring price of unsubsidized RE in many developing countries have also affected the level of diffusion and adoption of modern bioenergy systems use. Nonetheless, the diversity of biomass resources and energy extraction methodologies accounts for its vitality in RE application and decarbonization of power sector.

Biogas is one of the RE energy sources obtain from the category of biomass with biodegradable characteristic. Examples of such sources are waste dung from domestic animals, human feces, waste water, industrial slurries, biogenic component of municipal solid waste (MSW) and food waste from eateries. Biogas is methane rich combustible chemicals with distinctive high energy value. Biogas offers a technically realistic energy substitute in rural areas and helps mitigate a number of the consequences of wide-ranging biomass energy use [115,116]. In the recent past, efforts have been sustained in many developing countries to increase the level of biogas consumption for energy production. A broad consensus now exists as regards to the undisputed suitability of biogas for clean energy production. This has given biogas a better focus on any debate involving the promotion of RE for sustainable development. Today, several initiatives promoting large-scale and family-size biogas production and utilization exist in developing countries. Some recent research studies [117] have in addition established the possibility of using biogas for hybrid renewable energy implementation. Apart from biogas feedstock, agricultural residue is another important bioenergy sources widely used today. Agricultural residues comprise of waste materials generated from post farming harvesting activities and domestic in addition to industrial food processing wastes. Wastes from varieties of food and cash crops have been used as major source of energy in recent times. Examples of the residues which have gained wider application for the purpose of energy production are presented in Table 1. The residues are mostly exploited for energy in dried form as solid biomass. There are different kinds of technologies such a gasification, combustion and pyrolysis which are available for electricity production using biomass. In rural areas of developing countries, majority of the inhabitants are farmers which could promote community involvement in the production of bio-feedstock for power generation. Understandingly, the fact that energy density of crop residues is quite low is undisputed and most of power plants utilizing these residues are usually operated in small-power scale. Therefore, conclusion can be drawn that a hybrid system involving biomass using agricultural residue could be essential in the vicinity of rural areas where the resources are available.

An assortment of forest biomass such as wood waste from tree barks, sawdust, forest trim waste and forest logging residues are available for bioenergy consumption as well. Generally, conventional biomass, such as woodfuel for energy has received a attention especially in many developing countries. In urban areas of developing countries, electricity supply to households is in higher percentage compared to rural districts. The condition in rural areas is that woodfuel and charcoal can be acquired with minimum cost compared to fossil based kerosene and LPG for cooking. The high reliance on conventional biomass for energy is mirrored by the fact that 80% of the wood harvested in developing

Table 1
Agricultural crops and their residues.

Agricultural crops	Residue(s)
Maize (corn)	Straw, stalk, cob
Palm fruit	Empty fruit bunch,
Rice	Straw, husk
Sorghum	Stalk, head threash
Millet	Stalk
Coconut	Shell
Wheat	stalk
Sugar cane	Bagasse

countries and approximately 90% in Africa is used purposefully for fuelwood [118–120]. Besides, charcoal exploitation in the developing regions of the world is also on the increase [121–123]. Forest bioenergy resources have been identified as one of the RE energy sources suitable for hybrid power system configuration. Presently, a spreading intention on the application of HRES for power generation especially a kind of hybrid system involving biomass system may in due course explore forest wood to be a potential source. Looking at the current situation of energy challenges in developing countries, firewood is prone to remain an important fuel for another long period of time. The planting and self-regeneration density of forest trees in developing countries is quite low due to high exploitation frequency at different phases of succession. Control of forest trees in many developing countries especially in Africa is porous and larger part of non-forest trees are exhaustively harvested for firewood. To effectively promote forest wood for modern energy use in developing countries, government should promote a clear and secure policy framework on forest funding, development and exploitation control as absolute requisites.

5.2. Solar energy

Global solar radiation is one of the main sources of energy with potential effect for RE utilization and GHGs reduction. Solar radiation varies from one region to another throughout the world and it could also exhibit a zonal-wise variation within the region as revealed in Fig. 5. This difference in the natural potential of solar radiation at different geographical locations can be regarded as being the fact that exploitable potential differ with respect to the intensity of solar radiation. Effective solar radiation data at a given geographical location is, for all intents and purposes, important for development and analysis of solar energy projects [124]. As a result, numerous applications utilizing solar systems as substitute for conventional fossil-based energy uses exist. Foremost among the applications are solar cookers, water heater, and space heating and cooling systems in buildings. Modern solar energy technologies are cost effective and user-friendly. Utilizing the thermal energy of solar radiation can help reduce the present rate of deforestation [125–127] in developing countries and make a better contribution to sustainable development. As nations embark on development of sustainable energy systems, solar energy is a potential source which must be harnessed adequately to guarantee energy supply security and reliability. Since the potential to exploit any opportunity presented by solar radiation directly depends on the period of sunshine, then during winter, viability of solar energy potential decreases. A major approach towards resolving this challenge is an application of a hybrid power system integrating different energy sources and if possibly a back-up battery system for energy storage.

5.3. Wind energy

A wind energy system is a structural energy arrangement to utilize the kinetic energy of a blowing wind using an aerodynamic machine. Wind energy for electricity has played a very significant role in small-scale electricity at distributed generation level in wind rich regions of the world. In many developed countries like USA [129], Canada [130] and Denmark [131] wind generators are also being integrated to national grid systems. Regions where winds are potentially strong and more stable, such as offshore and high altitude positions are preferred locations for wind farms [132]. Output generated from a wind turbine is determined by area of the turbine blades, wind speed and wind density of the surrounding air. Wind power assessment is a major prerequisite for wind power exploitation because it determines the investment potential. Decisions regarding investment in wind electricity could be difficult to reach if comprehensive data systems are not available or adequate. Sustainable site selection for wind farm and efficient wind system conversion are significant considerations for optimal wind energy system management. A correct quantification and categorization of the available wind resources in any given geographical location is crucial to design a wind farm optimally, enlightening the investors by way of the required confidence in financial feasibility and risk assessment [134].

Very few developing countries have sustained investment in wind electricity especially China, South Africa, Brazil and India. Developed and developing countries are striving towards increasing installed capacity of wind power systems to achieve commercialization in the quest to develop the technology. However, serious financial backing and political reforms are required for enhancing aggressive development of wind power technologies in developing countries. A good example of such political enrichment mechanism is the case of China where considerable political support for the incursion of wind power development has been rising as shown in Fig. 6. Since the installation capacity increased over some period of time, then it can be said that the political agenda is yielding results. More to this, some countries with



Fig. 5. Four zones of solar energy resources in Tibet, China [128].

rapidly growing investment potency for wind energy exploitation have adopted some combination of approaches which include subsidy for investment cost, RE portfolio standard, tax exemption, institution of subsidized price of energy from wind systems and compulsion for utilities to generate power from wind-produced electricity. Therefore, integration of these strategies will tend to promote wind energy use for HRES expansion in developing countries.

5.4. Hydropower

Globally, there is lot of interest to exploit hydropower for electricity due to its clean and less operating and maintenance cost. Hydropower can also be referred to as hydraulic power. This kind of power is generated using the potential energy of gravitational force of flowing water. One basic fact about water especially the one that can be utilized for electricity generation is that it is not evenly distributed throughout the surface of the earth. This is why some regions have better potential for hydroelectricity than others while those without hydro source have to explore alternative means for energy production. To utilize hydro source for electricity production there must be the presence of water head level at certain height above the plain level ground. This requirement can be created in case of artificially created dam and may be naturally available in cases of natural dams with little financial requirement for modifications. Hydroelectricity productions have different potential scales ranging from micro (few kilowatts) to large (in megawatt or gigawatts). Increasing commonality in the use of dam of various sizes for electricity generation can be attributed to several benefits which could be derived from water sources as summarized in Table 2. Recent studies on hydropower focus on different aspects which include power generation from dams used for other activities [135], small electric potential [136,137], hydraulic modeling [138], hydropower policy support [139], and regional potential assessment [140]. In addition, large numbers of literatures [141–148] have also examined the uses of hydro for hybrid power implementation with reasonable feedback especially in rural districts. Convincingly, hydroelectricity shall continue to be one of the dominant systems in the scene of interest towards the exploitation of RE to foster different sorts of development.

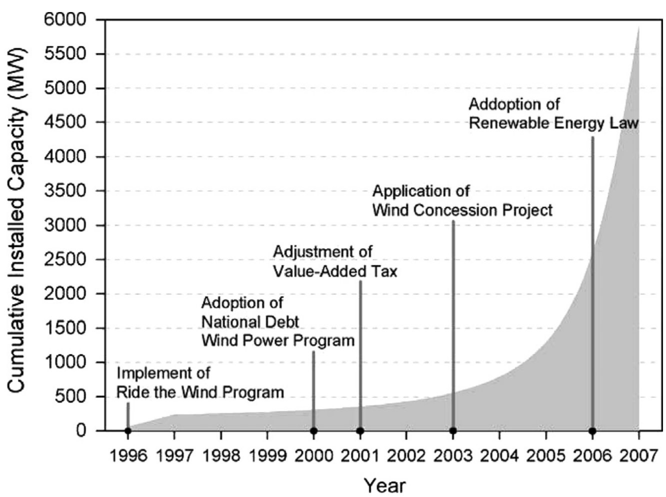


Fig. 6. Political milestones for wind power development in China [134].

6. Important issues in hybrid electric power systems design

6.1. System sizing and optimal configuration

Energy resources are very imperative from the economic and political perception for the whole world. This is why technological transformation in energy systems is exceedingly significant and an

Table 2
Advantages and disadvantages of the hydropower [120,121].

Advantages	Disadvantages
Economic aspects	
Provides low operating and maintenance costs	High upfront investment
Provides long life span (50–100 years and more)	Precipitation
Provides reliable service	Requires long-term planning
Includes proven technology	Requires long-term agreements
Instigates and fosters regional development	Requires multidisciplinary involvement
Provides highest energy efficiency rate	Often requires foreign contractors and funding
Creates employment opportunities and saves fuel	
Social aspects	
Leaves water available for other uses	May involve resettlement
Often provides flood protection	May restrict navigation
May enhance navigation conditions	Local land use patterns will be modified
Often enhances recreation	Waterborne disease vectors may need to be checked
Enhances accessibility of the territory and its resources	Requires management of competing water uses
Improves living conditions	
Sustains livelihoods (fresh water, food supply)	
Environmental aspects	
Produces no pollutants but only very few GHG emissions.	Inundation of terrestrial habitat
Enhances air quality	Modification of hydrological regimes
Produces no waste	Modification of aquatic habitats
Avoids depleting non-renewable fuel resources	Water quality needs to be managed
Often creates new freshwater ecosystems with increased productivity	Temporary introduction of methyl-mercury into the food chain needs to be monitored/managed
Enhances knowledge and improves management of valued species due to study results	Species activities and populations need to be monitored
Helps to slow down climate change	Barriers for fish migration, fish entrainment
Neither consumes nor pollutes the water it uses for electricity generation purposes	Sediment composition and transport may need to be monitored/managed

inevitable undertaking that researchers need to deal with [151]. In this regard, HRES have been accepted in the field of energy science as one of the promising technologies for RE utilization. The most two key tasks in problems linking to the design and implementation of HRES are sizing and optimal system configuration. Sizing and optimization in hybrid system design are mutually exclusive criteria for curtailing the cost involved so as to ensure that the load energy needs are fully covered. In designing of a hybrid system, the sizing of the components and the control approach must be suitably analyzed [152]. In respect to this demand, several researches have been implemented while others proposed some techniques for sizing and optimization of hybrid energy systems. Del Real et al. [153] presented a method of evaluating the optimal element sizing of a hybrid power system which incorporates a wind system, batteries and hydrogen storage system using a mathematical formulation, 'energy hub' concept. Rachid et al. [154] also presented a deterministic approach to verify the suitability of hybrid system sizing for selecting the optimal number of units required to minimize the cost of energy supply. The study conducted by Garcia and Weisser [155], verified the possibility of using a Linear Programming method with fixed dispatch to determine the size of grid units and dispatch in a hybrid wind–diesel system incorporating hydrogen storage with the intention to minimize cost taking a one-year time series data of hourly wind speed and electricity demand. Research is still ongoing in this area of important concern especially as the world is moving toward commercializing renewable energy systems in the aspiration to achieve global energy supply security.

Furthermore, optimal system configuration of a hybrid energy system is to attenuate intermittent effects produce when using RES under different weather conditions. It however helps in proper integration of the energy components, cost reduction and minimizes the necessity for energy storage systems. Consequently, the basic objective is optimal design of a hybrid system for reliable and economical supply of the electric load [156] to consumers. Researchers [157–159] have used genetic algorithms (GA) for evaluating the optimal configuration cost of a hybrid energy system. The result obtained from the study indicated a good system performance and effective cost scenario. An optimal system configuration is one of the several phenomenal concepts in hybrid power system. The optimization of wind–solar–battery hybrid system was established in the study conducted by [160]. Authors [161–163] underpinned iterative optimization technique (loss of power probability method) for optimal hybrid system configuration. For the same purpose of optimization, reference [164] proposed integration of stochastic modeling with numerical optimization for realization of more robust hybrid energy scheme. This particular method helps in reducing the overall cost of hybrid system implementation and performances. Therefore, regardless of the methodology used, what is significant is that an applicable and robust hybrid system should be designed to perform reliably even under the influence of some uncertainties.

6.2. Load profile study

In order to deal effectively with design problems related to hybrid power system, a proper load profile study of case study area is important. The load profile helps to reveal variations in power demand at various instances in days, months as well as seasons. A fluctuation in a typical load profile of any given community is usually in line with operation of domestic appliances and public facilities as well as business engagements. Designs of hybrid system for off-grid location require appropriate survey of load to balance between energy demand and supply including optimum cost control.

6.3. Software application for simulation and optimization of hybrid systems

Apart from various mathematical models used in analyzing the behaviors of different elements of hybrid systems, simulation and optimization softwares have also been found useful for varieties of applications. Areas of application include design, control strategy, economic optimization and multi-objective optimization. Many software packages have emerged but the most commonly used is Hybrid Optimization Model for Electric renewable (HOMER) [165–167]. HOMER has been used in many optimization analyses of HRES involving PV system, microhydro system, diesel generators, wind turbines, electrolyzer, fuel cell and hydrogen tank. This software is developed by the National Renewable Energy Laboratory (NREL) in the United States. Another useful software is improved Hybrid Optimization by Genetic Algorithms (iHOGA) which is a programme developed for hybrid energy system simulation and optimization. iHOGA formerly known as HOGA [168] is employed mainly in systems of hybrid renewable electrical energy involving (DC and/or AC) and/or Hydrogen. iHOGA has a very good reliability model for resources, economic and components. It can also resolve some complex issues relating to hybrid systems using Genetic Algorithms. It could also deal with multi-objective optimization approaches such as handling of emissions and minimization of present net cost of a hybrid system. HYBRID2 [110–171] is another software package widely used for optimization as well as performing comprehensive economic analysis and long term performance of a hybrid system. Other softwares that can be used for the same or closely related purposes are Transient Energy System Simulation Program (TRNSYS) [171], hydrogen energy models (HYDROGEMS) [172,173], hybrid system simulation models (HYBRIDS) [174], Solar simulator (SOLSIM) [146,175], INSEL [147], RAPSIM (Remote Area Power Supply Simulator) [176,177] and SOMES [178]. The uses of any of these software packages for simulation and optimization task are highly determined by the nature of input data characteristics and the task for which the software is designed to perform.

7. Conclusion

Based on this review objective, drivers encouraging the uses of HRES have been discussed. In addition, benefits of exploring the technique for power generation have also been presented. Up-to-date approaches to simulation and optimization of HRES using different software packages are also presented as one of the crucial issues involving series of analysis which must be undertaken to design a robust system with reasonable efficiency and operation means. Taking into consideration the escalating global needs for energy to sustain modern developments and reduce constraint to access energy in developing countries, energy supply system expansion has become a serious concern. However, efforts are still needed to be tailored towards promoting RE development. On this perception, it could be better suggested that HRES application for energy supply particularly in off-grid locations should be promoted. Long as the price of energy is a very key factor, therefore promoting design mechanisms with potential to lower cost is a very crucial factor because it could justify the consumption guides of energy resources. HRES have been used for such objectives. Purposefully to encourage massive deployment of HRES in some emerging developing countries, legislative and socio-political resolutions can also be regarded as inevitable instrument. Such legislative support need brings into limelight approaches which could bring down cost of energy from renewables.

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